CU COMAE: A NEW FIELD DOUBLE-MODE RR LYRAE, THE MOST METAL POOR DISCOVERED TO DATE [1]

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ABSTRACT

We report the discovery of a new double-mode RR Lyrae variable (RRd) in the field of our Galaxy: CU Comae. CU Comae is the sixth such RRd identified to date and is the most metal-poor RRd ever detected. Based on BVI CCD photometry spanning eleven years of observations, we find that CU Comae has periods $P_0=0.^d5441641(\pm0.0000049)$ and $P_1=0.^d4057605(\pm0.0000018)$. The amplitude of the primary (first-overtone) period of CU Comae is about twice the amplitude of the secondary (fundamental) period. The combination of the fundamental period of pulsation P_0 and the period ratio of $P_1/P_0=0.7457$ places the variable on the metal-poor side of the Petersen diagram, in the region occupied by M68 and M15 RRd's. A mass of 0.83 $M_\odot$ is estimated for CU Comae using an updated theoretical calibration of the Petersen diagram. High resolution spectroscopy (R=30,000) covering one full pulsation cycle of CU Comae was obtained with the 2.7 m telescope of the Mc Donald Observatory, and has been used to build up the radial velocity curve of the variable. Abundance analysis done on the four spectra taken near minimum light ($0.54 < \Phi < 0.71$) confirms the metal poor nature of CU Comae, for which we derive [Fe/H]$=-2.38 \pm 0.20$. This value places this new RRd at the extreme metal-poor edge of the metallicity distribution of the RR Lyrae variables in our Galaxy.

Subject headings: stars: abundances – stars: fundamental parameters – stars: horizontal-branch – stars: individual (CU Comae) – stars: oscillations – stars: variables: other

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[1]Based on data obtained with the 1.52 m telescope of the Bologna Observatory in Loiano, the Southwestern University 40 cm telescope, and the 2.7 m telescope of the McDonald Observatory

1. Introduction

Double-mode RR Lyrae variable stars (RRd) play a fundamental rôle in astrophysics because they can be used to estimate the mass and the mass-metallicity relation of horizontal branch stars, and because they can provide information on the direction and rate of evolution across the horizontal branch. RRd's are variables which pulsate both in the fundamental and first overtone radial pulsation modes. The evolutionary interpretation of the double-mode phenomenon suggests that these stars are changing their pulsation mode while evolving across the RR Lyrae instability strip. The mixing of the two pulsation modes produces cycle-to-cycle amplitude changes and a large scatter in the observed light curves, much larger than accounted for by observational errors alone. First discovered in 1977 (AQ Leo, Jerzykiewicz & Wenzel 1977), about 40 RRd's have been detected so far in a number of globular clusters of our Galaxy (e.g. M15: [Fe/H] = –2.12, M68: [Fe/H] = –1.99, IC4499: [Fe/H] = –1.26 on the Carretta & Gratton 1997, CG97, metallicity scale). Less than a hundred are hosted in a number of dwarf spheroidal (Draco: [Fe/H] = –1.83, Sculptor: [Fe/H] = –1.58, from Mateo 1998, transformed to the CG97 metallicity scale) and irregular galaxies of the Local Group; in particular 73 double-mode RR Lyraes have recently been detected by the MACHO experiment (Alcock et al. 1997) in the Large Magellanic Cloud (LMC). However, double-mode RR Lyraes seem to be a rather rare event in the field of our Galaxy where only 5 RRd's have previously been detected (Jerzykiewicz & Wenzel 1977; Clement, Kinman & Suntzeff 1991; Garcia-Melendo & Clement 1997; Moskalik 1999). All of the double-mode RR Lyraes have been so far generally found in metal poor stellar systems ([Fe/H] $\lesssim -1.3$ dex, CG97 scale, or –1.5 dex, Zinn & West 1984 scale). The metal abundance estimated by Clement et al. (1991) for three of the 5 Galactic RRds known so far (–1.70, –1.72, –1.60 for AQ Leo, RR VIII-58 and RR VIII-10 respectively, on the CG97 metallicity scale, corrected from −1.90, −1.91 and −1.81, on Zinn & West 1984 scale) confirms this finding. However, since the metallicity distribution of the RR Lyrae variables in the Galaxy extends to metal abundances both much lower and higher than in globular clusters, it is very important to identify RRd's among the field RR Lyrae population in order to test the mass-metallicity relation on a much wider metallicity interval. Applying the ΔS method (Preston 1959) to low resolution spectroscopic observations of RRd's in the bar of the LMC, Bragaglia et al. (2000) inferred metallicities in the range of −1.09 to −1.78 dex (or to −2.24 including one star with lower weight), and confirm that the LMC field RRd's follow the mass-metallicity relation defined by the Galactic cluster double-mode pulsators. However, with so few RRd stars identified in the field of our Galaxy, it is not possible to assess whether Galactic field RRd's actually obey the same mass-metallicity relation defined by the globular cluster RRd's. The discovery of any new Galactic field RRd helps set important constraints on the mass-metallicity relation; the discovery of this particular extremely metal-poor RRd also sets a new boundary condition.

In this paper, we present results based on new photometric data for the RR Lyrae variable CU Comae (CU Com) taken from 1995 to 1999, combined with published photometry of this object taken from 1989 to 1994 (Clementini et al. 1995b), together with high resolution spectroscopy obtained in 1999, that covers an entire pulsation cycle. Section 2 presents the observations and data sets. In section 3, we give our results from the analysis of the entire photometric data-set of CU Com (467 V, 172 B, and 167 I data points), which spans 11 years of observations. In Section 4 we report the results of our spectroscopic analyses. We have both derived a radial velocity curve of the full pulsation cycle (Section 4.1) and performed an elemental abundance analysis of the spectra of CU Com taken near minimum light (Section 4.2). In section 5, we estimate the mass of CU Com using a new theoretical calibration of the Petersen diagram (Petersen 1973), summarize the main derived quantities of CU Com, and discuss the impact of this new discovery on both the mass metallicity relation, and on the evolutionary interpretation of the double-mode pulsation for RR Lyrae variables.

2. Observations and reductions

In the fourth edition of the General Catalogue of Variable Stars (Kholopov et al. 1985, GCVS4) CU Com ($\alpha_{2000} = 12^h24^m47^s$, $\delta_{2000} = 22^o24'29''$) is classified as an *ab* type RR Lyrae with P=$0.^d416091$ and amplitude of the photographic light variation of 0.5 mag. Clementini et al. (1995b) presented observations of CU Com taken during the years 1989-1994. Their V light curve (121 data points) has a sinusoidal shape (see their fig. 3b) reminiscent of a *c* type pulsator; however, the region around maximum light is split into two separate branches about 0.15 mag apart. They also derived a shorter period of P=$0.^d405749$ and a larger (V) amplitude of 0.58 mag compared to the GCVS4 values. The irregular nature of the CU Com light curve is confirmed by the much less sampled photometry of Schmidt, Chab & Reiswig (1995, 26 data points, see their fig. 2). However, neither the Clementini et al. (1995b), nor Schmidt et al. (1995), photometries were sufficient to address the issue of whether CU Com was exhibiting double-mode or non-radial mode pulsation (Olech et al. 1999), or whether it might be affected by the Blazhko effect (Blazhko 1907). A new observing campaign was conducted on CU Com from 1995 to 1999, collecting data on several consecutive nights of each run and in two-three runs about one month apart, to test both the possibility of double-mode or non-radial mode pulsation (which both are known to occur on cycle-to-cycle timescales), and of the Blazhko effect (whose periodic modulation of the lightcurve typically has timescales of tens of days). Moreover, during the 1999 campaign, coordinated observations at the 1.52 m telescope of the Bologna Observatory in Loiano, at the 60 cm of the Michigan State University, and at the 40 cm of the Southwestern University were organized, to obtain continuous photometry with time coverage longer than 12-16 hours. High resolution spectroscopy was also secured in order to check whether CU Com might be the component of a spectroscopic binary system, to obtain its radial velocity curve, and to perform an abundance analysis of the variable. Uneven weather conditions at the various sites prevented us from getting long-span photometric observing nights, however we succeeded to obtain simultaneous photometry and spectroscopy with the 40 cm Southwestern University and the 2.7 m McDonald telescopes, on the night of 1999, February 12.

2.1. The photometry

The new photometric observations of CU Com were obtained in 21 nights from March 1995 to April 1999. They consist essentially of BVI CCD observations in the Johnson-Cousins system obtained with the Loiano 1.52 m telescope operated by the Bologna Observatory, and are complemented by 17 V and 8 B frames obtained with the Southwestern University 40 cm. The journal of the new photometric observations is given in Table 1. Observations at the 1.52 m telescope were obtained with two different instrumental set-ups, (i) with an RCA CCD for direct imaging having a 4.3×2.7 arcmin^2 field of view and a 0.5 arcsec/pixel scale, and (ii) with BFOSC (Bologna Faint Object Spectrograph & Camera) mounting a Thomson 1k×1k CCD with 0.5 arcsec/pixel scale giving a field of view of 9.6×9.6 arcmin^2. A filter wheel for the Johnson-Cousins photometric system was used with both set-ups. A 2.3×2.8 arcmin^2 CCD image of the CU Com field is shown in Figure 1. Four stars, beside CU Com, are marked on the image. These are non variable objects which were used as reference stars. The light curve of CU Com is derived in terms of differential magnitude with respect to these comparison stars (whose constancy has been accurately checked), hence no concern arises when observations were performed in non strictly photometric conditions. Observations at the 40 cm Southwestern University telescope were obtained using standard Johnson B and V filters and a Pictor 416XT CCD camera coupled to a Celestron f/6.3 focal reducer. This configuration gives a scale of 0.8 arcsec/pixel resulting in a 7.4×10.1 arcmin^2 field of view. Data were pre-reduced and instrumental magnitudes of the variable and its comparison stars were derived by direct photon counting using standard routines for aperture photometry in IRAF[9]. The photometric data were tied to the standard photometric system through observation of 35 standard stars selected from Landolt (1983, 1992). Calibrated magnitudes of the 4 comparison stars are given in Table 2. Comparison stars are identified in column 2 of the table by their numbers on the 1.2 version of the *Hubble Space Telescope* Guide Star Catalogue (GSC1.2). Within the quoted photometric uncertainty the V magnitude of star C1 given in Table 2 agrees with the value published by Clementini et al. (1995b), however the present value, being the average of several measurements obtained in four independent calibration nights, supersedes the 1995 estimate. The B, V, and I magnitudes of CU Com relative to the primary comparison star C1 are listed in Table 3 along with the Heliocentric Julian date at mid-exposure. Only data corresponding to the first night of observations of the 1995-1999 span are listed in the table. According to the errors quoted in Table 2 we estimate that the photometric accuracy of each individual data point is ± 0.03 mag in V and B, and ± 0.04 mag in I. For sake of homogeneity, instrumental magnitudes of CU Com and of its comparison stars in the 1989-1994 data published by Clementini et al. (1995b), were all re-measured in order to reduce any systematic effect which might arise in the analysis of the photometric data from inhomogeneities in the magnitude measuring procedure. The full photometric data set including the re-measured Clementini et al (1995b) photometry is published in the electronic edition of the

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Journal.

2.2. The spectroscopy

CU Com is the first double-mode RR Lyrae for which high resolution spectroscopy is available. Fifteen spectra evenly covering the full pulsation cycle of CU Com were obtained with the cross-dispersed echelle spectrometer at the coudé f/32.5 focus of the Harlan J. Smith 2.7 m telescope at the McDonald Observatory in West Texas during the nights of 1999, February 12 and 13. Seeing conditions during the nights varied from 1.5″ to 1.7″. Exposures of a Thorium-Argon lamp were taken at beginning, middle and end of each night, in order to secure the absolute wavelength calibration. Observations of the radial velocity standard star HD 58923 (RV=+17.8 km s^{-1}, Wilson 1953) were also obtained in order to use them during the cross-correlation measure of the radial velocities of CU Com and to set the radial velocity zero point.

The "2d-coudé" spectrograph (Tull et al. 1995) was operated using the E2 echelle grating (52.6759 grooves mm^{-1} with a blaze angle of 65.293) which yields a two-pixel resolving power at the CCD of R=$\lambda/\Delta\lambda$=63 000. Our wavelength coverage extended from 3670Å to 9900Å (with inter-order gaps in wavelength coverage redward of 5600Å) with the data from about 4400 to 5300 Å, and from 3924 to 8465 Å used in the radial velocity and metallicity determinations, respectively.

Given the faintness of our target ($<V>\sim$ 13.3 and $V_{min} \sim$ 13.6 mag) and the severe constraints on the exposure length (exposures of CU Com could not exceed 20-30 min in order to avoid phase blurring on the pulsation cycle of this short period variable star), we used a 1010 μm slit (which projects to 2 arcsec on the sky) and performed a 2×2 binning during the read-out of the CCD in order to increase the S/N ratio. The FWHM measured from the ThAr comparison lamp lines is $\sim$ 0.2Å. The data were taken on a 2048×2048 thinned, grade 1 Textronix CCD.

Data were reduced using standard IRAF processing tools to correct and calibrate for various detector effects. The overscan region of each image was used to determine the bias level to subtract from each frame. We then trimmed the overscan region from the individual images. Identification of the locations of "bad" pixels was made by means of long exposure dark frames as well as flat field frames. Bad pixel values were replaced using interpolated values from neighbouring pixels. We then divided the stellar and comparison lamp spectra by a scaled "flat field" image (comprised of 20 spectra taken with a quartz lamp through a blue-pass filter) in order to correct for the relative differences in pixel response of the detector. The minimum order separation was 10 arcsec, leaving sufficient interorder background free of contamination from starlight in order to adequately remove the (small) scattered light contribution. Cosmic ray excision was performed using *lineclean*.

We extracted the flux in the individual orders of the two-dimensional data to obtain one-dimensional summed spectra of the stellar and comparison lamp spectra. Using the Th-Ar comparison lamp emission spectra, we determined and applied the dispersion relation to the stellar spectra, interpolating in time over shifts in the comparison line positions on the chip through the course of a night. We verified that the resulting wavelength solutions gave correct positions of known atmospheric emission and absorption features on each spectrum. Geocentric and heliocentric Julian dates were computed and the information implanted in the file headers. The information was then used to compute the corrections to the observed radial velocity due to the diurnal, monthly, and yearly motions.

3. Analysis of the photometric data

Using the differential photometry of CU Com with respect to the reference star C1 and the full 1989-1999 data-set (the present new photometry together with Clementini et al, 1995b, one) we performed a period search with GRATIS (GRaphycal Analyzer TIme Series), a code being developed at the Bologna Observatory which employes two different algorithms: (a) a Lomb periodogram (Lomb 1976, Scargle 1982) and (b) a best-fit of the data with a truncated Fourier series (Barning 1962). The adopted period search procedure was to perform the Lomb analysis on a wide period interval first, and then to use the Fourier algorithm to refine the period definition and find the best fitting model. The period search employed each of the complete B, V and I data-sets. Figure 2 shows the periodograms of CU Com V, B, and I data respectively, obtained using the Lomb algorithm to identify the most probable frequency of the data on a wide period interval of 0.2-0.7 day. The highest peaks at ω=2.46 (P$\sim$0.406 d) correspond to the primary periodicity of the data; the two lower peaks at ω=1.46 and ω=3.46 respectively, are aliases of the primary periodicity, while the peaks at ω=1.84 are the signature of a second periodicity present in the data.

We then reduced the interval around the primary periodicity using the Fourier algorithm to find the best fit. The period obtained using a three harmonics best-fitting Fourier series on the V data, and a two harmonics series on the B and I data is P=$0.^d405759\pm0.000001$. Shown in Figure 3, are the V, B, and I light curves of CU Com obtained phasing the data according to this periodicity, together with the best fitting models. Filled circles mark data obtained with the 40 cm Southwestern University telescope.

The *r.m.s.* deviation from the best-fitting model is $\pm$0.083 mag in V, $\pm$0.109 mag in B and $\pm$0.056 mag in I. These residuals are much larger than expected from observational errors alone ($\pm$0.03 mag in V and B, and $\pm$0.04 mag in I) and provide us with clues that a second periodicity may be present in the data. The amplitude of the light variation ranges from 0.63 to 0.30 mag in V, from 0.82 to 0.45 in B, and from 0.41 to 0.20 in I. Data corresponding to consecutive nights show that the amplitude variation takes place on a cycle-to-cycle timescale (see Di Tomaso, 2000 for details). This occurrence definitely rules out the Blazhko effect as explanation of the irregular behaviour of CU Com. Since the residuals and amplitude of the light variation of CU Com cannot be described by a single periodicity, and the variation occurs on cycle-to-cycle basis, we proceeded looking for a second periodicity in the data on timescales of the order of one day. Data were prewhitened using the best fitting models in Figure 3 and a new period search was performed on the residuals with respect to the models. Figure 4 shows the periodograms of the residuals of the V, B and I data, respectively, obtained from the Lomb algorithm on a wide period interval of 0.1-0.9 d. Strong peaks are present at ω=1.84 (P$\sim$0.54 d) in all the three periodograms, which clearly mark the second periodicity present in the data of CU Com. We further refined the secondary period by restricting the period search interval and using a 3 harmonics best-fitting Fourier series in V and a 2 harmonics model in B and I, and then performed an iterative refinement of both primary and secondary periodicities. At the end of the trial procedure (conducted on the V, B, and I data, independently) the final adopted periodicities of CU Com are: $P_1=0.^d4057605\pm$ 0.0000018 and $P_0=0.^d5441641\pm$ 0.0000049. We also conducted another, independent period search on the CU Com V data-set using the Date Compensated Discrete Fourier Transform program (DCDFT, Ferraz-Mello 1981) and the CLEANEST routine (Foster 1995). Its results ($P_1=0.^d405760\pm$ 0.000001 and $P_0=0.^d544166\pm$ 0.000003 with the DCDFT; $P_1=0.^d405761\pm$ 0.000001 and $P_0=0.^d544164\pm$ 0.000003 with CLEANEST) fully confirm the periodicities found by the GRATIS algorithms.

The ratio of the first to second period of CU Com is P_1/P_0=0.745658 $\pm$ 0.000007 which is a typical value for double-mode RR Lyrae stars. The top panels of Figure 5, 6 and 7 show the V, B and I light curves of CU Com phased according to the primary (first-overtone) period of pulsation $P_1=0.^d4057605$ and the epoch of maximum light $E=2450142.^d5860390$. The central panels give the light curves of the primary period after prewhitening of the secondary (fundamental) period $P_0=0.^d5441641$, and the bottom panels show the light curves of the secondary period after prewhitening of the primary periodicity. The *r.m.s.* deviations of the best fitting models of the prewhitened data (central panels of Figure 5, 6 and 7) are about halved with respect to the original data (0.049 mag in V, 0.069 mag in B and 0.034 mag in I). The amplitudes of the primary variation are 0.43 mag, 0.55 mag and 0.27 mag in V, B and I respectively, and the corresponding amplitudes of the secondary (fundamental) variation are 0.22, 0.25 and 0.14 mag. Since the B and V residuals are still slightly too large when compared to the quoted photometric errors, we investigated whether a third periodicity might be present in the data. Indeed, several low peaks around $P\sim0.^d233$ were found, both with GRATIS and CLEANEST, when searching for this additional periodicity (P_2) the V, B and I data, independently. The highest peaks of each individual data set give periods in the range $0.^d232439$–$0.^d232587$ (ω=4.2995–4.3022), and the corresponding primary and secondary periodicities we found are in the ranges $P_1=0.^d405757$–$0.^d405762$ and $P_0=0.^d544164$–$0.^d544173$, respectively. While inclusion of these third periodicities, (after prewhitening each individual data set according to its P_0 and P_2 periodicities) marginally reduces the *r.m.s.* deviations of the best fitting models (from 0.049 to 0.040 mag, from 0.069 to 0.059, and from 0.034 to 0.030 in V, B and I, respectively), residuals are almost identical if data are prewhitened according to second and third periodicities which are the average of the P_0 and P_2 values found from each of the three data set independently (0.047 mag in V, 0.065 mag in B, and 0.034 mag in I). On the other hand, these "large" residuals might partially be caused by the lower accuracy of some of the photometric data (particularly data obtained in full moon nights with very poor seeing conditions). In order to investigate this possibility further we restricted the analysis to the data where the difference between comparison stars (C1 and C4, in particular) remained constant within $\pm$0.03 mag, which is the typical photometric error both in V and B. The data-set was thus restricted to 378, 116, and

134 data-points in V, B, and I, respectively. While periodicities found with this data subset fully confirm the results obtained with the complete data-set, the residuals are indeed slightly reduced (0.043 in V, 0.067 B, and 0.031 in I, respectively). A search for a third periodicity was conducted also on this small data-set. Again several low peaks around $0.^{d}233$ were found. Inclusion of a third period (which is the average of the individual P_2 values found from the V, B and I data, independently) in the analysis of the data reduces the residuals to the fit to 0.38 mag in V, 0.059 mag in B and 0.025 mag in I. However, the patterns of the peaks in the $0.^{d}233$ area are somewhat confused. Overall, this third periodicity is not very strongly supported by the data.

4. Analysis of the spectroscopic data

4.1. The radial velocity curve

Radial velocities were measured from the reduced wavelength calibrated spectra of CU Com using a cross correlation technique (*fxcor* in IRAF). Twelve orders containing weak metal lines (the best suited to measure radial velocities) in the spectra of CU Com were cross-correlated against the same orders in the spectra of the radial velocity standard star HD 58923. Table 4 lists the derived heliocentric radial velocities of CU Com and corresponding errors, along with the heliocentric phases of the spectra, computed according to the final adopted primary period of pulsation and the epoch of CU Com ($P_1=0.^{d}4057605$ and E=2450142.5860390). Neither splitting of lines nor double cross correlation peaks were observed, which would otherwise provide a hint of a spectroscopic binary system. Errors in the measured radial velocities of CU Com (see last column of Table 4) are larger than found for 2 other RR Lyraes observed in the same observing run (CM Leo and BS Com, an RRc and an RRab, respectively). These slightly large uncertainties (typical errors of 3 instead of 2 km s^{-1}, in spite of CU Com being about half magnitude brighter than CM Leo) can be attributed to the extremely low metal abundance of the star (see Section 4.2). The bottom panel of Figure 8 shows the radial velocity curve of CU Com obtained phasing the data according to its primary period of pulsation, while the top panel shows the simultaneous V light curve obtained with the 40 cm Southwestern University telescope. The shape and amplitude of the radial velocity curve (A_{RV}= 32.73 km s^{-1}) are typical of a *c*-type pulsator. The systemic velocity (γ) of CU Com was calculated by integration of the radial velocity curve on the full pulsation cycle and corresponds to -54.13 km s^{-1}.

4.2. The metallicity of CU Com

Four spectra of CU Com taken at/near the minimum light ($0.54< \Phi < 0.71$) were used to measure the metal abundance of the variable from the following line analysis procedure.

First, we derived the effective temperature T_{eff} from the dereddened B$-$V and V$-$I colors of CU Com at minimum light. A reddening value of E(B−V)=0.023 mag was estimated for CU Com from Schlegel, Finkbeiner & Davis (1998) reddening maps. Table 5 lists the dereddened B−V and V−I photometric colors corresponding to the four exposures of CU Com close to minimum light, derived from the B and V light curves simultaneous to the spectroscopic data and from the total I light curve (since no simultaneous I photometry is available), along with the corresponding temperatures as estimated using the color-temperature calibration and procedure of Clementini et al. (1995a). The average *photometric* temperature we derive is $T_{\rm eff}$ = 6286 ± 112 K where according to Clementini et al (1995a; see their Section 3.4.2) the mean temperature derived from individual $(B-V)_0$'s was lowered by 49 K, and that from the $(V-I)_0$'s was lowered by 97 K, before averaging them together, to tie them to the V−K-temperature calibration for RR Lyrae stars, since this calibration is not affected by discrepancy between synthetic (Kurucs 1993) and observed colors (see Figure 3 of Clementini et al, 1995a) and it is less metallicity dependent (see Fernley, 1989, and reference therein). Within the errors, there is no difference between the mean temperature estimated using colors at minimum light derived from the total B, V, and I light curves and the temperature obtained from the simultaneous photometry.

As an alternative approach, temperatures were also estimated by fitting the profile of the Hβ line (the Hα profile is usually used in this technique but was not observed with the adopted wavelength set up) in the four spectra. We devised the following effective technique to remove the characteristic wavelength response induced by the echelle blaze function, a pseudo-flat fielding was obtained by dividing the spectrum of the order including Hβ by the average of the two adjacent orders (this division was made using the pixel values, ignoring the wavelength calibration); before this division was made, cosmic rays and strong absorption lines (other than Hβ) were excised, and the spectra of the adjacent orders were gaussian-smoothed with a FWHM of 1 Å. This procedure works quite well because the instrumental response has no strong wavelength dependence other than the echelle blaze function. The continuum was traced far from the center of Hβ and normalized to a value of unity, and the Hβ feature and surrounding regions were then compared with line profiles obtained following the same precepts described in Castelli, Gratton & Kurucz (1997). Figure 9 shows the result of this comparison obtained using the Kurucz (1993) model atmospheres, with the overshooting option switched on (these models are used for consistency with the analysis of Clementini et al. 1995a; temperatures obtained with the Kurucz model atmospheres without overshooting are lower by about 250 K). The average *spectroscopic* temperature we obtained for the four spectra taken close to minimum light is 6400±150 K. Within their quoted uncertainties photometric and spectroscopic temperatures agree well. The temperature from Hβ is about 100 K higher than the photometric one. Adopting the photometric temperature in our analysis permits us to stay on the same scale of Clementini et al. (1995a), so that the new abundances can be directly compared with those and avoids any lingering doubts about the effectiveness with which we determined the continuum region near Hβ. Furthermore, the photometric temperature is less sensitive to the adopted set of model atmospheres. We then summed up the 4 individual spectra (after excision of the cosmic rays and shift to zero radial velocity). The coadded spectrum was convolved with a Gaussian having a FWHM of 0.3 Å to enhance the S/N and allows us to measure faint, unsaturated lines with confidence. Finally, we measured equivalent widths of 15 Fe I and 8 Fe II lines on the coadded spectrum. Table 6 gives the linelist, the assumed $\log gf$'s and the corresponding EW's we measured. Only the first ten lines of the table are shown. The full table is available in electronic form upon request to the first author. A full discussion of the reliability of these adopted atomic parameters to determine abundances of RR Lyrae variable stars can be found in Section 4.1.1 of Clementini et al. (1995a).

We obtained average abundances of [Fe/H]=-2.35 ± 0.026 (with σ=0.10 dex) from Fe I lines, and [Fe/H]=-2.40 ± 0.028 (with σ=0.08 dex) from Fe II lines, using a stellar atmosphere model with the following parameters: $T_{\rm eff}$ = 6286 K, a surface gravity of $\log g = 3.2$, and a microturbulent velocity of V_t = 3.5 km s^{-1}. The model parameters we derived, with the exception of the very low metallicity we find, are typical of c/d-type RR Lyrae's at minimum light (see also Clementini et al. 1995a). Standard spectroscopic abundance constraints (abundance results which show no trends with either line strength or excitation or ionization state), were easily satisfied in the analysis, confirming the adopted photometric temperature. Figure 10 shows the comparison of the spectrum of CU Com near the Mg b lines, with analogous spectra for two other RR Lyraes (X Ari, [Fe/H]=-2.52; and ST Boo, [Fe/H]=-1.80) from Clementini et al. (1995a). Iron-group lines in the spectrum of CU Com have strength similar to those in the spectrum of X Ari, and are much weaker than those in ST Boo, in agreement with the metallicity given by our analysis. Note that while weak lines in CU Com appear stronger than in X Ari (due to the slightly larger metal abundance), the stronger lines (noticeable the Mg b ones) are somewhat shallower: this is due to the lower microturbulent velocity of CU Com (an RRd) with respect to X Ari and ST Boo (both RRab's). Uncertainties in the derived abundances are mainly due to possible errors in the atmospheric parameters ($\pm$ 100 K in $T_{\rm eff}$, $\pm$ 0.3 dex in $\log g$, $\pm$ 0.5 km s^{-1} in V_t, and $\pm$0.2 dex in [A/H]) and on the adopted model atmospheres (Kurucz 1993). Our estimate of the random error contribution (including errors in measuring individual lines) is 0.13 dex. However, the adopted model atmospheres may contribute an additional 0.15 dex. Thus, our conservative estimate of the metallicity and of the total error for CU Com is [Fe/H]=-2.38 ± 0.20. This metallicity is on the same scale of CG97 and Clementini et al. (1995a) for RR Lyrae variables. On these same scales X Ari, the most metal poor RR Lyrae, of any type, known so far, has a metal abundance of -2.52 dex and M15, the most metal poor globular cluster where RRd variables have been found, has a metal abundance [Fe/H]=-2.12. CU Com thus becomes the most metal deficient double mode RR Lyrae ever detected.

Table 7 shows the abundance ratios with respect to iron we derive for a few other elements. As a comparison, in the last column are listed the same abundance ratios obtained by Clementini et al. (1995a) for X Ari: we find a very similar abundance pattern, namely an overabundance of $\alpha-$elements by about 0.4 dex, and a large deficiency of Mn and of Ba. This is the typical abundance pattern for very metal-poor stars ([Fe/H]< -2). We also get a very low Al abundance from the resonance lines, a result shared by other extremely metal-poor stars (Gratton & Sneden 1988).

5. Discussion and conclusions

CU Com is the sixth double-mode RR Lyrae identified in the field of our Galaxy. As is true of most of the RRd's known so far, the amplitude of the primary (first-overtone) period is about twice the amplitude of the secondary (fundamental) period. Final periods and epoch, as well as the average quantities derived for CU Com from both the photometric and the spectroscopic analyses are given in Table 8. According to the period ratio P_1/P_0=0.7457 and the secondary period (P_0), CU Com falls on the metal poor side of the Petersen diagram, in the region populated by the M68 and M15 double-mode pulsators (see Figure 11). This is confirmed by the extremely low metallicity ([Fe/H]=-2.38 ± 0.20) derived for CU Com from the abundance analysis of the spectra taken at minimum light, making it the most metal poor double mode RR Lyrae known so far.

An estimate for the mass of CU Com has been obtained from the Petersen diagram, following Alcock et al. (1997) and adopting Bono et al. (1996) theoretical mass-calibration. Following the suggestion by Cox (1991) that the inclusion of new opacity evaluations (Rogers & Iglesias 1992) in the computation of pulsation models allows one to reconcile pulsational and evolutionary predictions for the stellar mass of double mode RR Lyrae, Bono et al. (1996) investigated the Petersen diagram predicted for Oosterhoff I and Oosterhoff II cluster pulsators on the basis of their nonlinear convective pulsation models with updated input physics. The properties of these models, as well as the adopted physical and numerical assumptions, are extensively discussed in Bono & Stellingwerf (1994) and Bono et al. (1996, 1997a,b). The main result found by Bono et al. (1996) was that the Petersen diagram based on nonlinear computations is able to provide valuable constraints on the mass and on the luminosity level of double mode RR Lyrae belonging to Oosterhoff I and Oosterhoff II clusters.

The comparison between the predictions of Bono et al. (1996) and the location of CU Com in the Petersen diagram indicates for this star a mass larger than 0.80 $M_{\odot}$ (see Figure 11), placing it among the most massive double-mode RR Lyr's. In order to better constrain the "pulsational" mass of CU Com, new sequences of nonlinear models with 0.83 and 0.85 $M_{\odot}$, respectively, have been computed, using exactly the same code and the same physical inputs as in Bono et al. (1996). The behavior of these new models in the Petersen diagram is shown in Figure 11 (dashed and long-dashed lines) for the computed luminosity levels ($\log L/L_{\odot}$ = 1.72 and 1.81 for the 0.83 $M_{\odot}$ model, and only the $\log L/L_{\odot}$ = 1.81 level for the 0.85 $M_{\odot}$ model). CU Com, as well as most of the M68 and M15 RRd's, is very well fitted by the new pulsational models which indicate a mass of 0.830 $\pm$ 0.005 $M\odot$ and a luminosity level close to 1.81. A relation between the mass and the metallicity is known to exist among RRd variables in globular clusters and possibly in the field in our Galaxy, in Local Group dwarf spheroidals, and in the LMC (see Bragaglia et al. 2000). CU Com well fits that relation and extends it to the lowest metallicity end. In Figure 11 there are a couple of field RRd stars that are less massive then those in IC 4499, these are NSV09295 (Garcia-Melendo & Clement, 1997, the lowest filled triangle of Figure 11) and VIII-10 (Clement et al 1991). No metal abundance is available for NSV09295, while according to its metallicity VIII-10 is about 0.3 dex more metal poor than IC 4499 (see Introduction). Indeed, VIII-10 falls slightly off the mass-metallicity relation in Figure 7 of Bragaglia et al 2000. However, given the small number of RRd's in the field of our Galaxy we think that no firm conclusion can be reached on whether the Galactic field RRd's do or do not actually follow the same mass-metallicity relation of the cluster RRd's.

According to the evolutionary models consistent with ours (Cassisi et al. 1998, 1999) a stellar mass of about 0.8 $M_{\odot}$ is expected to populate the RR Lyrae gap for a metallicity Z=0.0001. Hence, the expected stellar mass populating the RR Lyrae instability strip in metal-poor globular clusters such as M15 and M68 is close to 0.80 M$\odot$ with a luminosity level between 1.75 and 1.8, depending on the assumed efficiency of element diffusion. Model isochrones by the same authors (Cassisi et al. 1998, 1999) suggest a turn-off age of 11.6 Gyr and a turn-off mass of 0.80 M$\odot$ for a red giant mass of 0.83 $M_{\odot}$ (when diffusion and mass loss are neglected) with the typical low metallicities of clusters such as M15.

Taking into account an α-enhancement contribution of $\sim$ 0.4 dex, which is typical of the lowest metallicity stars in the solar neighborhood and in globular clusters such as, for instance, M68 (see e.g. Carney 1996) which is also shared by CU Com (see Section 4.2), and including it in the global metallicity computation following the relation provided by Salaris et al. (1993), one would obtain for these stars a metallicity Z=1.5 $\times 10^{-4}$. This tiny metallicity increase with respect to Z=0.0001 is not expected to change the results of the pulsation analysis. On the other hand, model isochrones for Z=0.0002 predict an age ranging from 10.9 to 11.2 Gyr, depending on the efficiency of element diffusion, and a turn-off mass of 0.80 M$\odot$ for a red giant mass of 0.83 M$\odot$. Indeed, adopting this metallicity Cassisi et al. (1999) estimated an age of 11 $\pm$ 1 Gyr for M68. It is also worth noticing that the luminosity level of CU Com, of the M68 and M15 RRd's inferred from the Petersen approach is in good agreement with the evolutionary predictions one may extrapolate, for a mass of $\sim$ 0.83 $M_{\odot}$, from updated horizontal branch evolutionary models (Cassisi et al. 1998).

Thus, if the pulsational masses estimated from Figure 11 are correct, the M68 and M15 RRd's should have masses around 0.83 M$\odot$ and luminosities of about $\log L/L_{\odot}$= 1.81. This would imply that almost no mass loss occurs during the red giant branch evolution of these very metal poor cluster stars.

Unfortunately, no firm constraint on the red giant phase mass loss can be inferred from the large pulsational mass of CU Com because, at variance with the double mode pulsators in globular clusters, we do not have any information on its age, hence, on its turn-off mass. However, (i) given the similarity of CU Com mass with masses of double mode pulsators in M68 and M15, (ii) given its extremely low metal abundance, and (iii) given the direct dependence of mass loss upon metal abundance predicted by canonical mass loss relations such as those by Reimers (1975) or Maeder (1992), it is probable that CU Com has not lost a large amount of mass during its red giant branch evolution.

The synthetic horizontal branch distributions computed by Rood (1973) first showed the need for an average mass loss of about 0.2 $M_{\odot}$ prior to the horizontal branch phase, coupled to a $\sim$

10% dispersion of 0.025 $M_\odot$ in order to reproduce the color extension of the horizontal branch of metal poor globular clusters (see also Renzini & Fusi Pecci 1988, Chiosi 1998). Reimers (1975) empirical formula predicts that the mass loss needed to reproduce the observed horizontal branch morphologies at Z $\simeq$ 0.001 is obtained for a value of 0.40 $\pm$ 0.04 for the mass loss rate efficiency parameter η (see Renzini & Fusi Pecci 1988). Thus, if the 0.83 $M_\odot$ we derive for CU Com is correct, its turn-off mass could range from 0.83 $M_\odot$, in the case of no mass loss, up to 0.93 $M_\odot$ for an assumed mass loss of 0.1 $M_\odot$ (a reasonable assumption given the overall uncertainties). Correspondingly, CU Com age could range from $\sim$ 10 to 6.5 Gyr: the turn off ages of a 0.83 and a 0.93 $M_\odot$, respectively, according to Cassisi et al. (1998) models at Z=0.0002 and including diffusion.

In this framework, the implication of the high mass and low metallicity of CU Com on the evolutionary interpretation of the double-mode phenomenon is that, if its estimated metallicity and mass are correct, CU Com is a massive, overluminous RR Lyrae almost as old as M68, sharing the typical α-elements overabundance of very metal-poor stars, which started its horizontal branch evolution on the very red side of the instability strip and is now moving blueward across the strip while evolving from the *ab* to the *c* type region.

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REFERENCES

Alcock et al. (*The MACHO collaboration*) 1997, ApJ, 482, 89

Barning, F.J.M. 1962, Bull. Astron. Inst. Netherlands, 17, 22

Blazhko, S. 1907, Astron. Nachr., 175, 325

Bono, G., Caputo, F., Castellani, V., & Marconi M. 1996, ApJ, 471, L33

Bono, G., & Stellingwerf, R.F. 1994, ApJS, 93, 233

Bono, G., Caputo, F., Castellani, V., & Marconi M. 1997a, A&AS, 121, 327

Bono, G., Caputo, F., Cassisi, S., Incerpi, R., Marconi, M. 1997b, ApJ, 483, 811

Bragaglia, A., Carretta, E., Gratton, R.G., Clementini, G., & Di Fabrizio, L. 2000, AJ, submitted

Carney, B.W. 1996, PASP, 108, 900

Carretta, E., & Gratton R.G. 1997, A&AS, 121, 95, (CG97)

Cassisi, S., Castellani, V., degl'Innocenti, S., & Weiss 1998, A&AS, 129, 267

Cassisi, S., Castellani, V., degl'Innocenti, S., & Weiss 1999, A&AS, 134, 103

Castelli, F., Gratton, R.G. & Kurucz, R.L. 1997, A&A, 318, 841

Chiosi, C. 1998 in Stellar Astrophysics for the Local Group, eds. A. Aparicio, A. Herrero, F. Sánchez, Cambridge University Press, p. 1

Clement, C.M., Ferance, S. & Simon, N. 1993, ApJ, 412, 183

Clement, C.M., Kinman, T.D., & Suntzeff, N.B. 1991, ApJ, 396, 219

Clementini, G., Carretta, E., Gratton, R.G., Merighi, R., Mould, J.R., & McCarthy, J.K. 1995a, AJ, 110, 2319

Clementini, G., Tosi, M., Bragaglia, A., Merighi, R. & Maceroni, C. 1995b, MNRAS, 275, 929

Cox, A.N. 1991, ApJ, 381, L71

Di Tomaso, S. 2000, Thesis

Fernley, J.A., 1989, MNRAS, 239, 905

Ferraz-Mello, S. 1981, AJ86, 619

Foster, G. 1995, AJ, 109, 1889

Garcia-Melendo, E. & Clement, C.M. 1997, AJ, 114, 1190

Gratton, R.G., Sneden, C. 1988, A&A, 204, 193

Jerzykiewicz, M., & Wenzel, W. 1977, AcA, 27, 35

Kholopov, P.N. et al. 1985, *General Catalog of Variable Stars*, IV ed. (Moscow; GCVS4)

Kurucz, R.L. 1993, CD-ROM13 and CD-ROM18

Landolt, A.U. 1983, AJ, 88, 439

Landolt, A.U. 1992, AJ, 104, 340

Lomb, N.R. 1976, Ap&SS, 39, 447

Mateo, M. 1998, ARA&A, 36, 435

Maeder, A. 1992, A&A, 264, 105

Moskalik, P. 1999, in IAU Colloquium 176, in The Impact of Large-Scale Surveys on Pulsating Star Research, eds. L. Szabados & D. Kurtz, ASP Conf.Ser., in press

Nemec, J.M. 1985b, AJ, 90, 240

Nemec, J.M. 1985a, AJ, 90, 204

Olech, A,. Kaluzny, J., Thompson, I.B., Pych, W., Krzeminski, W. & Shwarzenberg-Czerny, A. 1999, AJ, 118, 442

Petersen, J.E. 1973, A&A, 27, 89

Preston, G.W. 1959, ApJ, 130, 507

Reimers, D. 1975, in Problems in Stellar Atmospheres and Envelopes, eds. B. Baschek, W.H. Kegel & G. Traving, Springer-Verlag, p. 129

Renzini, A., & Fusi Pecci, F. 1988, ARA&A, 26, 199

Rogers, F.J. & Iglesias, C.A. 1992, ApJ, 401, 361

Rood, R. T. 1973, ApJ, 184, 815

Salaris, M., Chieffi, A., & Straniero, O. 1993, ApJ, 414, 580

Scargle, J.D. 1982, ApJ, 263, 835

Schmidt, E.G., Chab, J.R., Reiswig, D.E. 1995, AJ, 102, 1766

Schlegel, D.J., Finkbeiner, D.P., & Davis, M. 1998, ApJ, 500, 525

Tull, R.G., MacQueen, P.J., Sneden, C., & Lambert, D.L. 1995, PASP, 107, 251

Walker, A.R. 1994, AJ, 108, 555

Walker, A.R., & Nemec, J.M. 1996, AJ, 112, 2026

Wilson, R.F. 1953, *General Catalogue of Stellar radial velocitie*, Carnegie Institution of Washington Publ. 601, Washington D.C.

Zinn, R.J., & West, M.J. 1984, ApJS, 55, 45

Fig. 1.— A 2.3 × 2.8 arcmin^2 CCD image of the CU Com field. The four stars marked beside CU Com are non variable objects which were used as reference stars to obtain differential measurements of the magnitude variation of CU Com.

Fig. 2.— Periodograms of the V, B, and I data of CU Com which identify the most probable frequency of the data (ω=2.46), the two aliases at ω=1.46 and ω=3.46, and a secondary periodicity at ω=1.84 (see text).

Fig. 3.— V, B, and I light curves of CU Com. Data are phased according to a primary (first-overtone) period of pulsation $P_1=0.^d405759$. The complete data-set spanning 11 years of observations (1989-1999) is plotted. Solid lines are the best fitting models used to fit the data. Filled circles mark photometric observations obtained with the 40 cm telescope simultaneous to the spectroscopic ones.

Fig. 4.— Periodograms of the residuals of the V, B and I data, respectively, which identify the most probable secondary frequency of the data (ω=1.84) and the two aliases at ω=2.84 and ω=3.84 (see text).

Fig. 5.— Light curve of the V data of CU Com phased according to the primary (first-overtone) period of pulsation $P_1=0.^d4057605$ derived at the end of the prewhitening procedure (top panel). The central panel shows the light curve of the primary (first-overtone) period after prewhitening of the secondary (fundamental) period $P_0=0.^d5441641$, and the bottom panel shows the light curve of the secondary (fundamental) period after prewhitening of the primary (first-overtone) period.

Fig. 6.— Same as Figure 5 for the B data-set of CU Com.

Fig. 7.— Same as Figure 5 for the I data-set of CU Com.

Fig. 8.— Radial velocity curve (bottom panel) and simultaneous V light curve of CU Com (top panel), obtained with the 2.7 m McDonald telescope and the 40 cm of the Southwestern University, respectively.

Fig. 9.— Comparison of the observed Hβ line profiles and synthetic spectra computed using the Kurucz (1993) model atmospheres, with the overshooting option switched on (see text). Labels indicate the spectra according to their identification in Table 5. The average temperatures we obtained for the four spectra taken close to minimum light is 6400 K±150 K.

Fig. 10.— A small section of the coadded spectrum of CU Com (near the Mg b lines), compared with spectra for two other RR Lyraes (X Ari, [Fe/H]=−2.52; and ST Boo, [Fe/H]=−1.80) from Clementini et al. (1995a). These two latter have been shifted vertically for clarity. Note that the iron-group lines in the spectrum of CU Com have strength similar to those in the spectrum of X Ari, and are much weaker than those in ST Boo, in agreement with the metallicity given by our analysis.

Fig. 11.— Position of CU Com on the Petersen diagram. Data shown in the figure are from Walker & Nemec (1996; IC4499), Walker (1994; M68), Nemec (1985b; M15), Nemec (1985a; Draco), Clement, Ferance & Simon (1993; AQ Leo, VIII-10, and VIII-58), Garcia-Melendo & Clement (1997; NSV09295), and Alcock et al. (1997; LMC). Dashed-dotted, solid and dotted lines represent Bono et al. (1996) pulsational models for masses of 0.65, 0.70 and 0.80 M$\odot$, and log L/L$\odot$= 1.72 (upper portion of the curves) and log L/L$\odot$= 1.81 (lower portions), respectively. The dashed and long-dashed lines show our new pulsational models for 0.83 M$\odot$ and 0.85 M$\odot$, respectively. Only the $\log L/L_{\odot}$= 1.81 luminosity level is shown in the latter case.

Table 1: Journal of the new photometric observations

Year	N.of Observations			Observed intervals
	B	V	I	(HJD−2452400000)
1995	8	16	7	49789 - 49846
1996	23	21	22	50130 - 50195
1997	14	27	16	50550 - 50551
1998	1	1		50842
1999	126	281	113	51220 - 51301
Tot	172	346	158	

Table 2: Magnitudes of the comparison stars

Star	N_{GSC}	V	B	I
C1	0144701247	14.08 ± 0.03	14.89 ± 0.03	13.19 ± 0.04
C2	0144700851	15.27 ± 0.03	15.88 ± 0.03	14.62 ± 0.04
C3	0144701207	15.12 ± 0.03	15.80 ± 0.03	14.40 ± 0.04
C4	0144701193	14.60 ± 0.03	15.31 ± 0.03	13.87 ± 0.04

Table 3: The photometric observations.*

HJD (−2400000)	ΔV	HJD (−2400000)	ΔB	HJD (−2400000)	ΔI
49789.3640137	−0.676	49789.3725840	−1.127	49789.3876953	−0.242
0.3811035	−0.665	0.4024110	−1.065	0.4169922	−0.209
0.3942871	−0.633	0.4328630	−1.048	0.4472656	−0.204
0.4106445	−0.618	0.4618910	−1.044	0.4763184	−0.227
0.4233398	−0.582				
0.4409180	−0.589				
0.4536133	−0.585				
0.4699707	−0.612				

*The complete version of this table which includes also the updated version of Clementini et al (1995) photometry is in the electronic edition of the Journal. The printed edition contains only a sample of the present new photometry

Table 4: The heliocentric radial velocities

Spectrum	HJD	Φ	RV km s^{-1}	Error km s^{-1}
W1	51222.750103	0.073	−69.94	3.97
W2	0.765833	0.112	−69.96	2.94
W3	0.780487	0.148	−69.17	3.75
W4	0.798555	0.192	−67.37	3.54
W5	0.820304	0.246	−61.83	2.90
W6	0.841913	0.299	−58.99	1.84
W7	0.868628	0.365	−54.85	2.94
W8	0.892935	0.425	−50.24	3.77
W9	0.916663	0.483	−48.41	4.45
W10	0.938504	0.537	−44.14	3.71
W11	0.961503	0.594	−41.50	2.14
W12	0.983263	0.647	−39.62	1.99
W13	51223.009931	0.713	−37.96	2.64
W14	0.894986	0.895	−56.13	2.56
W15	0.909752	0.931	−63.12	4.68

Table 5: Temperatures derived from CU Com dereddened colors at minimum light

Spectrum	Φ	$(B-V)_0$	$(V-I)_0$	T_{eff} $(B-V)_0$	T_{eff} $(V-I)_0$
W10	0.537	0.369	0.495	6305	6550
W11	0.594	0.400	0.506	6130	6513
W12	0.647	0.411	0.525	6070	6448
W13	0.713	0.355	0.519	6385	6470

Table 6: Linelist and measured EW's

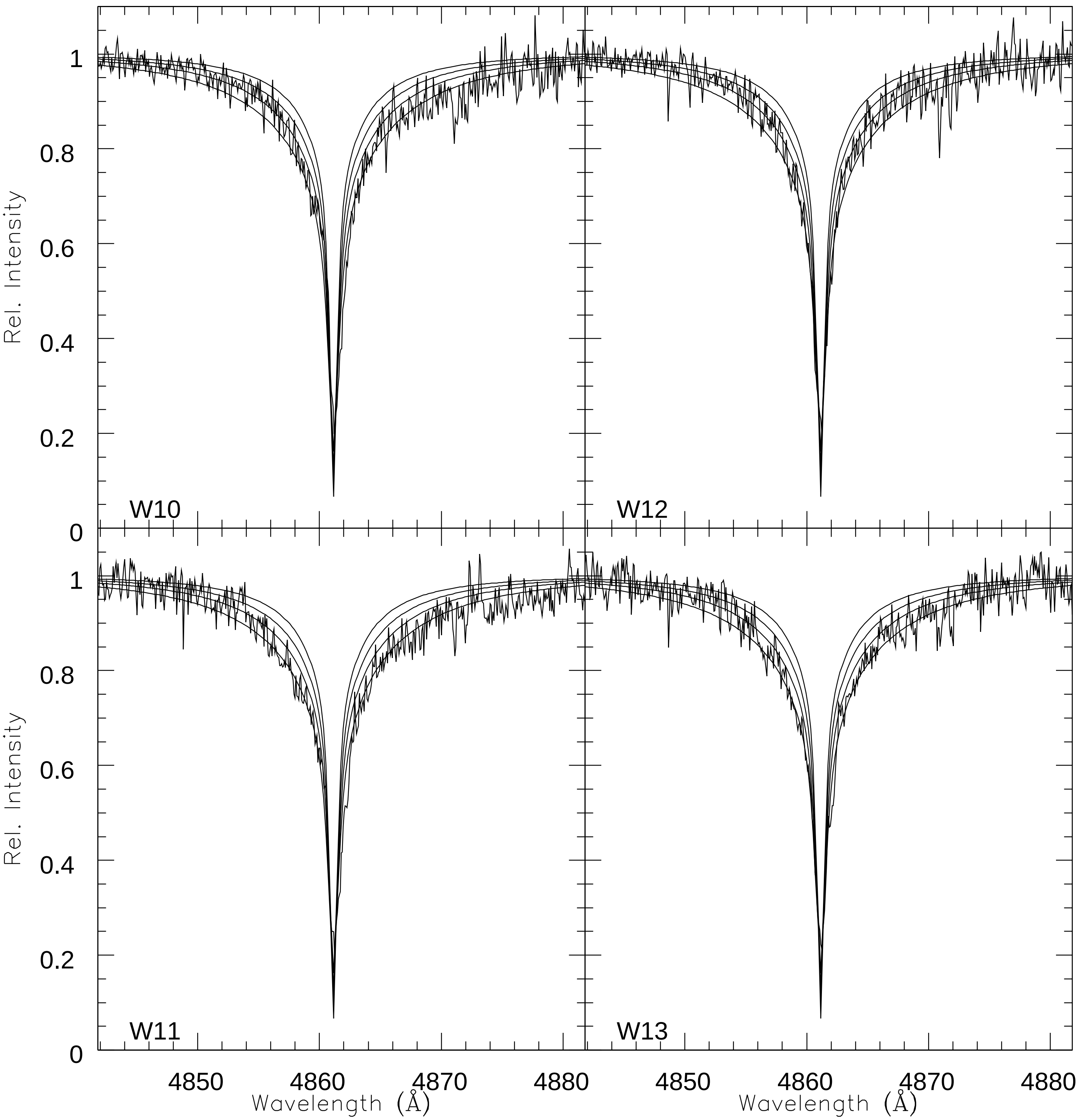
Element	λ	E.P.	$\log gf$	EW	$\log n$
Fe I	4005.24	1.56	–0.57	111.10	5.28
Fe I	4045.81	1.49	0.22	159.10	5.23
Fe I	4071.74	1.61	–0.02	137.50	5.23
Fe I	4132.06	1.61	–0.63	86.10	5.03
Fe I	4143.87	1.56	–0.44	102.70	5.03
Fe I	4235.95	2.43	–0.34	47.90	5.06
Fe I	4383.56	1.49	0.20	159.50	5.13
Fe I	4415.13	1.61	–0.61	109.40	5.28
Fe I	4427.32	0.05	–3.04	26.40	5.23
Fe I	4459.14	2.18	–1.28	14.80	5.13

Table 7: Average elemental abundances for CU Com and X Ari

		CU Com		X Ari
	n	mean	r.m.s	
[Fe/H] I	15	−2.35	0.10	−2.52
[Fe/H] II	8	−2.40	0.08	−2.48
[Mg/Fe] I	5	0.39	0.29	0.52
[Al/Fe] I	2	−0.99	0.07	−0.30
[Ca/Fe] I	7	0.29	0.15	0.45
[Sc/Fe] II	4	0.24	0.21	0.31
[Ti/Fe] II	11	0.46	0.15	0.34
[Cr/Fe] I	1	−0.22		−0.30
[Mn/Fe] I	3	−0.83	0.14	−0.81
[Sr/Fe] II	2	−0.21	0.04	
[Ba/Fe] II	1	−0.71		−0.75

Table 8: Properties of CU Com

Type	RRd
[Fe/H]	-2.38 ± 0.20
Epoch	$2450142.^{d}5860390$
P_1	$0.^{d}4057605 \pm 0.0000018$
P_0	$0.^{d}5441641 \pm 0.0000049$
P_1/P_0	0.745658 ± 0.000007
M	$0.830 \pm 0.005 M_\odot$
$< V >$	13.34
$< B >$	13.67
$< I >$	12.88
$< B > - < V >$	0.33
$< V > - < I >$	0.46
A_1(V)	0.43
A_0(V)	0.22
A_1(B)	0.55
A_0(B)	0.25
A_1(I)	0.27
A_0(I)	0.14
A_{RV}	32.73 km s^{-1}
γ	-54.13 km s^{-1}


Rel. Intensity
Rel. Intensity
W10
W12
W11
W13
0
0.2
0.4
0.6
0.8
1
4850
4860
4870
4880
Wavelength (Å)
Wavelength (Å)